EFFICIENCY OF *SOIL WASHING* IN REMOVING PETROLEUM HYDROCARBON RESIDUES

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Abstract

Soil contamination by petroleum hydrocarbon residues, particularly from used motor oil, requires effective and relatively simple remediation technology. This study evaluated the efficiency of pilot-scale soil washing using the non-ionic surfactant Polysorbate 80 to remove Total Petroleum Hydrocarbon (TPH) from artificially contaminated sandy soil. The contaminated medium was prepared by mixing commercial sand and used motor oil at a ratio of 85:15, resulting in an initial TPH concentration of 13.5039% or 135,039.42 mg/kg. Pilot-scale batch soil washing was conducted using a drum rotary agitator at 50 rpm with variations in Polysorbate 80 concentration (0.5%, 1.5%, and 2.5%), washing time (30, 60, and 90 min), and solid/liquid ratio (1:5, 1:10, and 1:15). TPH was analyzed using a gravimetric method, and the removal efficiency was calculated based on the difference between the initial and final concentrations. The results showed that soil washing removed TPH with efficiencies ranging from 68.72% to 92.40%. The highest efficiency of 92.40% was achieved at 1.5% Polysorbate 80, a 60 min washing time, and a 1:10 solid/liquid ratio. A low surfactant concentration of 0.5% also produced a high removal efficiency, reaching 89.66% at 30 min and a 1:10 ratio. In contrast, a 2.5% surfactant concentration combined with a short washing time produced the lowest efficiency, presumably due to stable emulsion formation and mass-transfer limitations. These findings indicate that pilot-scale soil washing with Polysorbate 80 is effective in removing TPH from sandy soils, particularly under low-to-moderate surfactant concentrations and a 30–60 min contact time.

Keywords: Drum Rotary Agitator, Used Oil, Polysorbate 80, Remediation, Soil Washing, TPH.

1. INTRODUCTION

Soil contamination by petroleum hydrocarbons remains a critical environmental issue due to the extensive use, storage, transportation, and disposal of petroleum-derived products. Petroleum hydrocarbons may enter the soil environment through oil spills, leakage from storage facilities, workshop activities, improper disposal of used lubricating oil, and accidental releases during petroleum handling. Once released into the soil, petroleum hydrocarbons can alter soil quality, reduce ecological function, and pose risks to groundwater and surrounding ecosystems. Total Petroleum Hydrocarbon (TPH) is commonly used as an aggregate parameter to represent a complex mixture of petroleum-derived hydrocarbons in environmental samples, including volatile and extractable hydrocarbon fractions (Kuppusamy et al., 2020).

Petroleum hydrocarbon contamination can alter the physical, chemical, biological, and geotechnical properties of soil, thereby reduce soil fertility and increase environmental risk. Recent reviews have emphasized that remediation of petroleum-contaminated soil requires the selection of suitable treatment methods based on contaminant characteristics, soil properties, and site conditions (Majeed et al., 2025).

The Decree of the State Minister of Environment No. 128 of 2003 regulates the technical requirements for the biological treatment of petroleum waste and petroleum-contaminated soil, indicating the need for proper management of soils with high petroleum hydrocarbon contamination (Kementerian Negara Lingkungan Hidup Republik Indonesia, 2003). In the context of remediation, soil washing can be applied as an *ex-situ* method to separate contaminants from the soil matrix using a liquid medium and mechanical processes (United States Environmental Protection Agency, 1996).

Compared with biological and thermal remediation approaches, soil washing offers a relatively rapid ex-situ treatment option because contaminants can be physically and chemically transferred from the soil matrix into the washing solution. This method is particularly suitable for coarse-textured soils, such as sandy soils, because contaminants are more accessible on particle surfaces and can be detached through the combined effects of washing solution, surfactant addition, and mechanical agitation. Therefore, soil washing is considered an appropriate treatment approach for petroleum-contaminated sandy soil, especially when the process is supported by surfactants that enhance hydrocarbon mobilization.

Polysorbate 80, also known as Tween 80, is a non-ionic surfactant that is relevant for petroleum hydrocarbon remediation because it can promote emulsification and micellar solubilization of hydrophobic contaminants. Caetano et al. (2024) reported that Tween 80 was effective in removing TPH from artificially contaminated soil containing used lubricant oil, while Afandi and Ratnawati (2025) also evaluated Polysorbate 80 for soil washing of sandy soil contaminated with used motor oil. These studies indicate that Polysorbate 80 has potential as a washing agent for petroleum-contaminated sandy soils, although its removal performance can vary depending on operating conditions such as surfactant concentration, washing time, and solid/liquid ratio.

According to Zhao et al. (2024), surfactant-based chemical washing is an effective approach to enhance the solubilization, desorption, and separation of petroleum hydrocarbons from contaminated soils. This finding aligns with Caetano et al. (2024), who demonstrated that the use of Tween 80 in soil washing is capable of removing TPH from used lubricating oil-contaminated soil with an efficiency of 80.7 ± 3.2%.

Soil characteristics also determine the success of soil washing. Lange et al. (2023) showed that hydrocarbon contamination in sandy soils can form a hydrocarbon film layer on the surfaces of mineral particles as well as micro- and macroaggregates. This condition necessitates the implementation of a soil washing process to detach TPH from the sand particle surfaces and transfer it to the liquid phase.

However, previous studies have mostly focused on laboratory-scale soil washing systems using relatively small soil masses and conventional mixing configurations. For example, Caetano et al. (2024) evaluated soil washing using an orbital shaker system, while Afandi and Ratnawati (2025) investigated artificially contaminated sandy soil at a smaller experimental scale. Limited information is available regarding the performance of pilot-scale batch soil washing using a drum rotary agitator for sandy soil contaminated with used motor oil. This gap is important because scale, mixing configuration, soil mass, and contact intensity can influence the detachment and transfer of petroleum hydrocarbons during the washing process.

Therefore, this study aims to evaluate the efficiency of pilot-scale soil washing using the non-ionic surfactant Polysorbate 80 for removing TPH from artificially contaminated sandy soil. The study focuses on the effects of surfactant concentration, washing time, and solid/liquid ratio on TPH removal efficiency using a batch drum rotary agitator system. The results are expected to provide technical insight into the application of Polysorbate 80-assisted soil washing for petroleum hydrocarbon removal from sandy soils and support the development of practical ex-situ remediation strategies.

2. MATERIALS AND METHODS

The overall experimental procedure is divided into three main phases, as illustrated in Figure 1. The research was conducted experimentally on a pilot scale using a batch system. The sample, an artificial spiked soil, was prepared from homogeneous commercial sand that had been sieved and mixed with used motor oil. The mixture ratio used was 85% sand and 15% used oil. After mixing, the samples were aged for two days to optimize the physico-chemical contact and bonding between the oil and the sand particles.

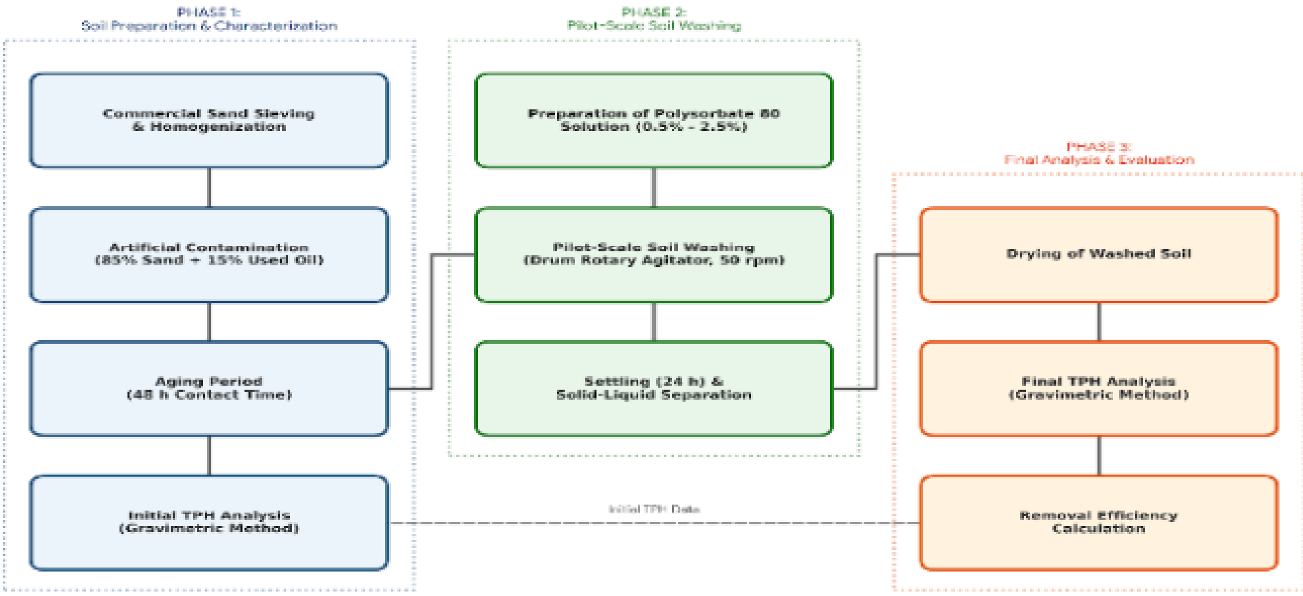

Figure 1. Flowchart of the hydrocarbon-contaminated soil remediation process using pilot-scale soil washing.

The soil washing process was carried out using a pilot-scale drum rotary agitator, as illustrated in Figure 2. The apparatus consists of a rotating drum driven by an electric motor via a chain drive system, which provides a constant and moderate mechanical attrition between the soil particles. During the experiment, the rotation speed was kept constant at 50 rpm. Each experiment utilized 2 kg of contaminated soil. The treatment boundaries comprising Polysorbate 80 concentration (0.5%-2.5%), washing time (30-90 min), and solid/liquid ratio (1:5-1:15) were structured based on the variable ranges of a Box-Behnken Design (BBD) framework. The selection of these parameter variations was based on the consideration that surfactant concentration, contact time, and the liquid-to-solid ratio are the primary operational factors in surfactant-assisted soil washing (Ayele et al., 2020; Caetano et al., 2024; Zhao et al., 2024).

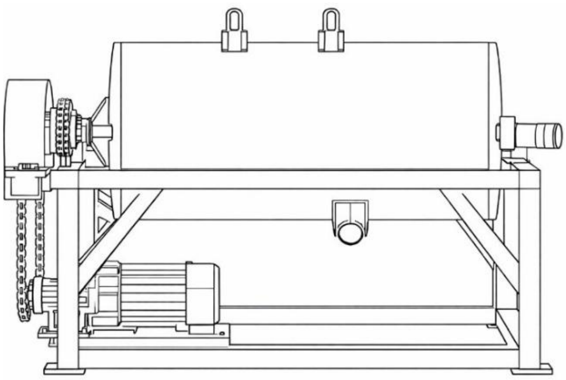

Figure 1. Schematic diagram of the pilot-scale drum rotary agitator used for the soil washing process.

After washing, the mixture was allowed to settle for 24 hours; the soil was then separated and dried, and the final TPH content was analyzed. TPH levels were analyzed gravimetrically using n-hexane extraction and residue weighing. The gravimetric approach was chosen because it can accurately quantify the oil and grease fraction or non-polar hydrocarbons in environmental samples through relatively simple procedures (Kuppusamy et al., 2020; United States Environmental Protection Agency, 2010).

Table 1. Variations in soil washing operating conditions

Variable	Unit	Level	Description
Polysorbate 80 concentration	% (v/v)	0.5,1.5, 2.5	Non-ionic surfactant used as washing agent
Washing time	min	30, 60, 90	Contact time in a rotary drum agitator
Solid-to-liquid ratio	w/v	1:5, 1:10, 1:15	Ratio of soil mass to washing solution volume
Agitation speed	rpm	50	Controlled variable
Washing solution pH	–	7.2–7.9	Observed pH range during the experiment

The quantitative removal efficiency of petroleum residues was calculated using Equation (1):

$$\text{Removal efficiency (\%)} = \frac{(C_0 - C_e)}{C_0} x\ 100\% \quad (1)$$

where C_0 is the initial TPH concentration and C_e is the final TPH concentration after soil washing.

3. RESULT AND DISCUSSION

Initial Characteristics of the Contaminated Soil

The artificially contaminated soil used in this study was dominated by the sand fraction at 99.180%, along with a silt fraction of 0.529% and a clay fraction of 0.91%. The dominance of the sand fraction supports the application of soil washing because coarse particles have a lower specific surface area and a lower adsorption capacity compared to fine fractions. Lange et al. (2023) explained that in hydrocarbon contaminated sandy soils, the mineral particle surfaces can be covered by a hydrocarbon film. Thus, the washing process is necessary to enhance hydrocarbon detachment from the sand particle surfaces.

The initial TPH concentration in the artificially contaminated soil was recorded at 13.5039%, equivalen to 135039.42 mg/kg. This value indicates that the soil was heavily contaminated and required further aggressive treatment. A summary of the initial physico-chemical characteristics of the sample is presented in Table 2.

Table 2. Initial physico-chemical characteristics of the artificially contaminated soil

Parameter	Value	Unit	Description
Sand	99.18	%	Dominant fraction
Silt	0.529	%	Low fine

Parameter	Value	Unit	Description
			fraction
Clay	0.291	%	Low fine fraction
Initial TPH	13.5039	%	Before soil washing
Initial TPH	135,039.42	mg/kg	Dry weight basis

Overall TPH Removal Efficiency

The soil washing results demonstrated that the use of Polysorbate 80 was able to significantly remove TPH, with efficiencies ranging from 68.72% to 92.40%. In Table 3 presents a summary of the washing efficiencies under representative operating conditions, covering the highest efficiency, the lowest efficiency, and a replication confirmation condition.

Table 3. Summary of soil washing efficiency under selected operating conditions

Polysorbate 80 (%)	Time (min)	Solid/ Liquid Ratio	TPH Reduction (mg/kg)	Removal Efficiency (%)
0.5	30	1:10	121069.99	89.66
0.5	60	1:15	122518.02	90.73
1.5	60	1:10	124769.67	92.40
2.5	90	1:10	123382.41	91.37
2.5	30	1:10	92798.68	68.72
0.5	30*	1:10	118942.72	88.08

*Replication test

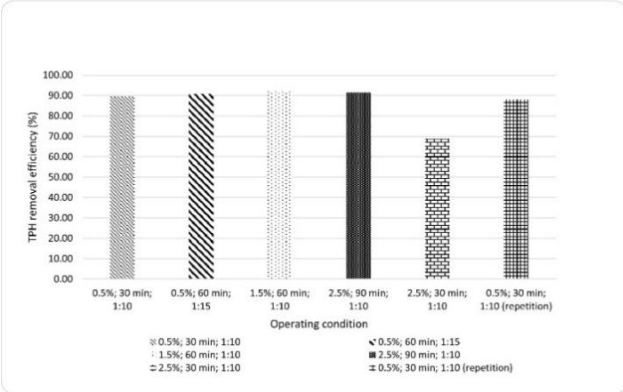

Figure 3. Pilot-scale soil washing efficiency under selected operating conditions.

Figure 3 presents the TPH removal efficiency under selected operating conditions. The figure highlights the highest removal efficiency, the lowest removal efficiency, and representative high-efficiency conditions obtained during the pilot-scale soil washing experiment.

Mechanism of Polysorbate 80 in TPH Removal

The conceptual mechanism of surfactant-enhanced soil washing in removing petroleum hydrocarbons from the sand matrix is illustrated in Figure 4. The effectiveness of Polysorbate 80 can be explained by its role as a non-ionic surfactant that significantly enhances the solubilization and mobilization of hydrophobic hydrocarbons. As shown in the initial phase, hydrocarbons physically bind to the surface of sand particles forming an oil film. The introduction of Polysorbate 80 molecules reduces the interfacial tension between the oil, water, and soil phases, facilitating the detachment of hydrocarbons from the soil particles.

Once detached, the hydrophobic tails of the surfactant encapsulate the TPH molecules, forming stable micelles (*micellar solubilization*), while the hydrophilic heads allow these micelles to be suspended in the aqueous phase. In sandy soils, this phase transfer mechanism is highly dominant and efficient because hydrocarbons are primarily attached to the outer surfaces of the macro-particles rather than trapped deep within micro-pores.

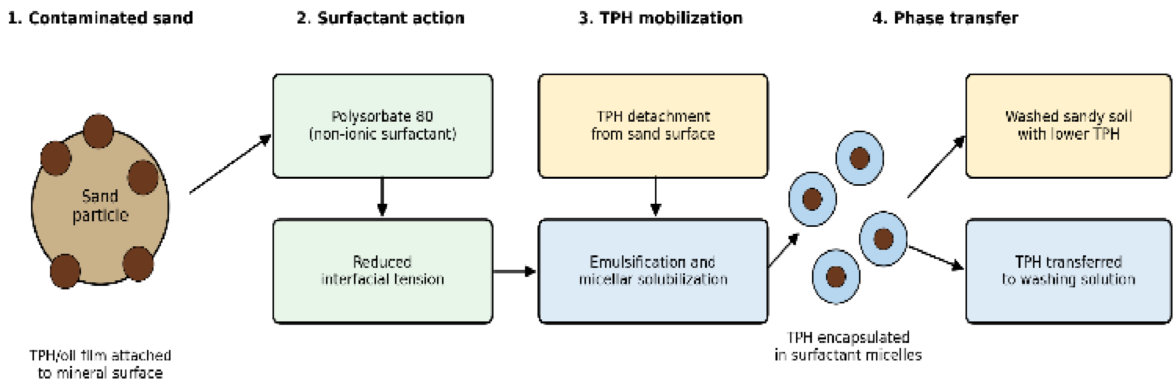

Figure 2. Proposed mechanism of TPH removal during pilot-scale soil washing using Polysorbate 80.

Recent studies on surfactant-enhanced remediation also highlight that surfactants improve petroleum hydrocarbon mobilization by reducing interfacial tension, increasing apparent solubility, and enhancing the transfer of hydrophobic contaminants from soil particles into the aqueous phase. This mechanism supports the high TPH removal efficiency observed in the present pilot-scale soil washing experiment (Xu et al., 2025).

Effect of Operating Parameters

The performance of the soil washing process is governed by the complex interplay between surfactant concentration, washing time, and the solid/liquid ratio. While the experiments were originally constructed following a Box-Behnken Design matrix involving central point repetitions to assess statistical error, an exhaustive statistical and mathematical modeling analysis falls outside the scope of this mechanistic discussion**.** Instead of presenting the full statistical matrix, this section explicitly extracts and evaluates only the most critical, representative conditions specifically showcasing the peak optimal performance, the lowest efficiency baseline, and the boundary interactions. This purposive extraction allows for a more profound and concise physical-chemical interpretation of the dynamic equilibrium inside the rotary drum without obscuring the core findings.

Surfactant concentration plays a pivotal role in determining the solubilization capacity of the washing fluid. The highest efficiency of 92.40% was achieved at a Polysorbate 80 concentration of 1.5%, a washing time of 60 minutes, and a solid/liquid ratio of 1:10. Zhao et al. (2024) stated that surfactants can enhance the solubilization, desorption, and separation of petroleum hydrocarbons from contaminated soils. Therefore, the surfactant concentration and contact time under these conditions were highly adequate to facilitate the kinetic desorption of TPH from the sand surfaces into the liquid phase.

Interestingly, a relatively low Polysorbate 80 concentration of 0.5% also demonstrated satisfactory performance, reaching 89.66% at a short contact time of 30 minutes with a 1:10 ratio. According to Ayele et al. (2020), the effectiveness of soil washing is influenced by a comprehensive coordination of the surfactant type, concentration, pH, agitation speed, and mixing duration. This high removal indicates that the 0.5% concentration is sufficient to reach or exceed the Critical Micelle Concentration (CMC) of Polysorbate 80 in this specific system. Once the CMC is reached, surfactant monomers aggregate to form micelles, maximizing the apparent solubility of the hydrophobic petroleum hydrocarbons.

Conversely, the lowest efficiency of 68.72% occurred at a 2.5% Polysorbate 80 concentration with a brief washing duration of 30 minutes at a 1:10 ratio. Zhao et al. (2024) emphasized that chemical washing efficiency is affected by operational factors and the equilibrium characteristics of the surfactant system. In this study, the addition of an excessively high surfactant concentration (2.5%) naturally and drastically increased the viscosity of the washing solution. This highly viscous solution required a longer agitation time and mechanical kinetic energy input to diffusively penetrate the sand macro-pores. Due to the overly short contact duration (30 minutes), this mass-transfer limitation triggered the retention of a rigid emulsion enveloping the solid particles, thereby severely degrading the removal performance.

Washing times of 30 to 60 minutes generally yielded optimal efficiencies. According to Caetano et al. (2024), contact duration, liquid/solid ratio, the quantity of washing stages, and surfactant concentration are the primary parameters determining TPH extraction efficiency. Because sandy soils exhibit weak adsorption binding forces, petroleum accumulation is dominant on the outermost particle surfaces, allowing optimal detachment to be achieved during the rapid initial desorption contact phase.

Furthermore, the high efficiency achieved in a relatively short time (30-60 min) highlights the critical role of the drum rotary agitator. Unlike conventional orbital shakers that solely rely on fluid hydrodynamics, the rotating drum induces a tumbling regime. This motion promotes intense particle-to-particle collision and abrasion (*mechanical attrition*). This physical scrubbing effect actively strips the hydrocarbon film off the sand grains, working synergistically with the chemical solubilization of Polysorbate 80 to accelerate the extraction phase.

A solid/liquid ratio of 1:10 provided consistent performance across several selected conditions. According to Caetano et al. (2024), the liquid/solid ratio is a crucial variable as it affects the intensity of hydrodynamic contact at the interface between solid particles and the extracting solution. A moderate ratio such as 1:10 provides a balance between removal efficiency and operational feasibility, preventing the mixture from forming a thick slurry (which limits particle mobility as seen in lower ratios like 1:5) and avoiding the generation of an unnecessarily large volume of secondary wastewater (as in 1:15).

Additionally, the pH range of the washing solution during the experiment remained stable at 7.2–7.9. Zhao et al. (2024) indicated that operating condition factors, including solution properties, play a significant role in the efficiency of surfactant-based chemical washing. This neutral to slightly alkaline condition is highly benefited by the non-ionic characteristics of Polysorbate 80, which does not undergo ionization in the aqueous phase, thus securing the soil mineral structure from damage due to extreme pH exposure.

Comparison with Previous Studies

The removal efficiency obtained in this

study was higher than that reported by Afandi and Ratnawati (2025), who found that Polysorbate 80 achieved a maximum TPH removal of 69.0% at 1.25% concentration during soil washing of sandy soil contaminated with used motor oil. The higher removal efficiency in the present pilot-scale study may be related to differences in operating conditions, particularly the use of a drum rotary agitator, optimized operating conditions, washing time, solid/liquid ratio, and contact intensity between soil particles and the surfactant solution.

Practical Implications and Limitations

The highest TPH removal achieved in this study was 92.40%, significantly reducing the initial concentration from 135,039.42 mg/kg to a residual of 10,269.75 mg/kg. According to the Indonesian Ministry of Environment Decree (Kepmen LH No. 128/2003), the ultimate cleanup target limit for treated petroleum-contaminated soil is strictly set at 10,000 mg/kg (1%). While the residual TPH in this study (1.02%) is remarkably close to fulfilling this regulatory threshold, it explicitly indicates that surfactant-assisted soil washing alone is highly effective as a primary mass-reduction step. However, to fully polish the soil for final environmental release, this process may need to be coupled with a subsequent mild treatment, such as biological remediation or advanced oxidation.

Future research direction

Future research should focus on the treatment and potential reuse of the washing solution, since surfactant-containing effluent may still contain dissolved petroleum hydrocarbons. The evaluation of real contaminated soils with different textures and organic matter contents is also necessary to determine the robustness of the process under field conditions. In addition, further comparison between synthetic surfactants and biosurfactants may provide insight into more sustainable remediation alternatives

4. CONCLUSION

Pilot-scale soil washing using a drum rotary agitator assisted by Polysorbate 80 proved effective as a primary mass-reduction step for removing TPH residues from the artificially contaminated sandy soil matrix with an initial concentration of 13.5039% (135039.42 mg/kg). The TPH removal efficiency was distributed within the range of 68.72–92.40%, where peak performance (92.40%) was achieved using a Polysorbate 80 dose of 1.5%, a washing time of 60 minutes, and a solid/liquid ratio of 1:10. The application of the surfactant at a low concentration (0.5%) proved reliable in triggering high desorption (89.66%), indicating that excessive surfactant dosing is not always necessary. Conversely, using a high dose of 2.5% for a short time (30 minutes) caused mass-transfer limitations due to the high viscosity of the solution, resulting in the lowest efficiency (68.72%). Overall, a combination of 30-60 minutes of mechanical agitation duration and a 1:10 solid/liquid ratio is recommended as the optimal operating condition, producing optimal removal efficiency with controlled chemical consumption

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